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CONSIDERATION OF SIMULATION PARAMETERS FOR BLUNT THICK BODIES IN RAREFIED HIGH-SPEED FLOWS

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ARO, Inc.

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VON KÁRMÁN GAS DYNAMICS FACILITY
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NOTICES

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FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

The current use of several different dynamic simulation parameters for correlating bluff body drag coefficient data is reviewed in terms of the need for a parameter which is both effective and does not contain any quantities whose values are uncertain in hypervelocity real-gas non-equilibrium flows. Such a nondimensional number or parameter is suggested and its effectiveness for correlating a variety of both previously published and new sphere drag data is assessed.

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NOMENCLATURE

C_D	Drag coefficient
d	Sphere diameter
H	Enthalpy
K	See Eq. (12)
Kn	Knudsen number

M	Mach number
R	Gas constant
Re	Reynolds number
Re_o	$\rho_\infty U_\infty d/\mu_o$
Re_w	$\rho_\infty U_\infty d/\mu_w$
Re_∞	$\rho_\infty U_\infty d/\mu_\infty$
S_w	$U_\infty/(2 R T_w)^{1/2}$
T	Temperature
U	Velocity
$\bar{V}_\infty$	See Eq. (8)
α	See Eq. (1)
γ	Ratio of specific heats
λ	Mean free path
μ	Absolute viscosity
ξ	See Eq. (14)
ρ	Mass density
Φ	See Eq. (14)
ω	Exponent in $\mu \sim T^\omega$

SUBSCRIPTS

2	Downstream of normal shock
fm	Free molecular value
o	Isentropic stagnation value
w	Average (forward) surface value
∞	Freestream value

SECTION I
INTRODUCTION

It is the purpose here to present some new sphere drag data and to discuss dynamic simulation or scaling parameters applicable in the study of bluff body drag under the rarefied-flow regimes characterized by near-free-molecule and merged-layer conditions. Specifically, sphere drag data are the subject of most attention because of their plenitude, but it is expected that the discussion is more generally applicable to bluff bodies as a class under the flow conditions assumed.

Concerning the two flow regimes, loose definitions for hypervelocity spheres may be given by the relations

$$\lambda_\infty/d = 0(1) \text{ for near-free-molecule flow}$$

and

$$\lambda_\infty/d = 0(0.1) \text{ for merged-layer flow}$$

Ignoring a factor which is of order unity for hypersonic Mach numbers, it is shown later that the comparable formulation in terms of Re_o is

$$Re_o = 0(1) \text{ for near-free-molecular flow}$$

and

$$Re_o = 0(10) \text{ for merged-layer flow}$$

The merged layer, of course, refers to merging of the bow shock wave and the stagnation region boundary layer. At the higher Reynolds or lower Knudsen numbers, flows in this class may be analyzed on the basis of continuum theory, but it is not appropriate to make the conventional thin-shock, thin-boundary-layer assumptions. As Knudsen number increases, progressing toward more rarefied flow, noncontinuum phenomena and considerable departure from adiabatic, thin-shock-layer conditions arise. However, the simpler, free-molecule flow model is not yet usable. To stress the noncontinuum nature of the flow, the present title includes only mention of the more rarefied gas-dynamic regime to be discussed. However, it is advantageous to include the more plentiful experimental data representing the merged-layer flow.

Sphere drag data have been published in many papers, but very few authors have dwelt at any length on the scaling parameter used to present the data. One reason has been the apparently satisfactory results obtained when using any of several parameters, as long as Mach numbers and wall-to-total temperature ratios did not vary too widely. Several theories for the near-free-molecule regime have been presented, but the range of Kn_∞ where the better of them give accurate predictions of C_D seems not to extend below approximately 0.5. Furthermore, they require the introduction of varying degrees of empiricism in adjusting the purely theoretical result to best fit available experimental data, and real-gas effects sometimes must be ignored in calculating fluid characteristics when experimental data are involved. Noting that possibly significant differences exist between full-scale and laboratory flow conditions applying to expensive aerospace systems, it behooves us to look more closely at the dynamic simulation parameters. We will examine those that have come to light in theoretical analyses or have proved reasonably effective in correlating experimental results, except that those requiring calculation of shock-layer conditions will be avoided, being uncertain or at least inconvenient for the flow regimes of interest herein.

SECTION II
SIMULATION PARAMETERS

In this section, the various leading simulation parameters are reduced to common terms insofar as possible. The Reynolds number, Re_w, is rather arbitrarily chosen as one of these recurrent quantities.

Sherman, et al. (Ref. 1) have suggested the parameter α_o, where

$$\alpha_o = Re_o (T_o/T_w)^{1/2} / \{4[U_\infty^2/(2RT_o)]^{1/2}\} \tag{1}$$

This may be rewritten as

$$\alpha_o = \frac{Re_o (\mu_w/\mu_o)(T_o/T_w)^{1/2} (\gamma R T_\infty)^{1/2} (T_o/T_\infty)^{1/2}}{4 U_\infty (\gamma/2)^{1/2}}$$

Then if $M_\infty >> 1$, i.e., $T_o/T_\infty \approx (\gamma-1) M_\infty^2/2$, and $\mu \sim T^\omega$,

$$\alpha_o = 0.250 \, Re_w (T_w/T_o)^{\omega-1/2} [(\gamma-1)/\gamma]^{1/2} \tag{2}$$

Kogan and Degtyarev (Ref. 2) have proposed the parameter S_w/Kn_∞. This may be expressed as

$$S_w/Kn_\infty = (M_\infty/Kn_\infty)[(\gamma/2)(T_\infty/T_w)]^{1/2}$$

$$= [Re_\infty/(1.26\,\gamma^{1/2})][(\gamma/2)(T_\infty/T_w)]^{1/2} \tag{3}$$

and, using $\mu \sim T^\omega$, this becomes

$$S_w/Kn_\infty = 0.561 \, Re_w (T_w/T_\infty)^{\omega-1/2} \tag{4}$$

Baker and Charwat (Ref. 3) and Kinslow and Potter (Ref. 4) made use of a parameter which may be defined as

$$Kn_w = 2^{1/2}\, Kn_\infty / \{1 - M_\infty [8\gamma T_\infty)/(9\pi T_w)]^{1/2}\}$$

$$= (1.78\, \gamma^{1/2} M_\infty/Re_\infty)/[1 + 0.531\, M_\infty \gamma^{1/2} (T_\infty/T_w)^{1/2}] \tag{5}$$

Then if $\mu \sim T^\omega$, $M_\infty >> 1$, and $T_w \approx T_\infty$,

$$1/Kn_w = 0.298\, Re_w (T_w/T_\infty)^{\omega - 1/2} \tag{6}$$

As seen by inspecting the second term in the denominator of Eq. (5), the requirement for high Mach number and cold-wall conditions is more specifically $0.531\ M_\infty \gamma^{1/2} (T_\infty/T_w)^{1/2} >> 1$. The latter is more likely to be true for full-scale or aeroballistic range conditions than in wind tunnels, so Eq. (6) must be used with caution.

Comparison of Eqs. (4) and (6) reveals that under hypersonic cold-wall conditions,

$$S_w/Kn_\infty \approx 1.88/Kn_w \tag{7}$$

The so-called rarefaction parameter or viscous-interaction parameter

$$\bar{V}_\infty = M_\infty [(\mu_w T_\infty)/(\mu_\infty T_w)]^{1/2}/Re_\infty^{1/2} \tag{8}$$

is included in this grouping because it has been shown to be effective in correlating drag coefficients of a variety of both blunt- and sharp-nosed slender bodies. The writers are not sure of its origin; the earliest work in which they have noticed the parameter is by Tsien (Ref. 5), who used the form $M_\infty/Re_\infty^{1/2}$. Substituting $\mu_w/\mu_\infty = (T_w/T_\infty)^\omega$ in Eq. (8), we obtain

$$\bar{V}_\infty = M_\infty [(T_\infty/T_w)/Re_w]^{1/2} \tag{9}$$

And if $M_\infty >> 1$, such that $M_\infty \approx [2\ (T_o/T_\infty)/(\gamma - 1)]^{1/2}$, then

$$\bar{V}_\infty \approx [2\,(T_o/T_w)/(\gamma - 1)]^{1/2}\ (1/Re_w)^{1/2} \tag{10}$$

A stagnation region Reynolds number should be considered in this discussion. For many years, the Reynolds number, Re_2, based on conditions immediately downstream of the normal part of the bow shock wave has been used to good effect in connection with blunt bodies, but its calculation in the flow considered here is complicated by major uncertainties concerning shock-layer conditions, specifically T_2 or μ_2. That problem is not notably less severe in any of the previous cases where T_o is a term in the parameter, so even use of the Reynolds number

$$Re_o = \rho_\infty U_\infty d/\mu_o \tag{11}$$

is not a completely satisfactory solution.

Cheng (Ref. 6) introducted a parameter which is, in the present case,

$$K^2 = [(\gamma - 1)/(2\gamma)] (Re_o/2) [(\mu_o/\mu_*) (T_*/T_o)] \tag{12}$$

with the starred quantities being reference values. If it is assumed that $\mu \sim T^{\omega}$, the final term in Eq. (12) becomes $(T_*/T_o)^{1-\omega}$. Further, taking $T_* = (T_2 + T_w)/2 \approx T_o/2$, it is seen that $K^2 = [(\gamma - 1)/4\gamma] Re_o (2)^{\omega-1}$. Alternately assuming $\mu = CT$, one finds $K^2 = [(\gamma - 1)/4\gamma] Re_o C$. Therefore, rather than discuss K separately it will be considered essentially equivalent to Re_o in this context.

Writing Eq. (11) as $Re_o = Re_w (T_w/T_o)^{\omega}$ it is observed that if $M_\infty >> 1$ such that $T_o/T_\infty \approx (\gamma - 1)M_\infty^2/2$, then

$$Re_o \approx (1.78/Kn_\infty) (T_\infty/T_o)^{\omega-1/2} [\gamma/(\gamma - 1)]^{1/2} \tag{13}$$

Therefore, under conditions where $\omega \approx 1/2$, $Re_o \sim 1/Kn_\infty$ for γ = const. This shows that the well-known problem of defining a satisfactory mean free path in a real gas, which often leads to substituting M_∞/Re_∞ for Kn_∞, also is avoidable when conditions justify choosing to use Re_o or K. In fact, there is some reason to avoid Re_∞, as well as Kn_∞, both of which require knowledge of μ_∞, because much of the hypersonic experimentation takes place in wind tunnels where T_∞ is very low, e.g., 20-30 °K, and μ_∞ is not accurately known at extremely low (or high) temperatures.

Perhaps the better course is to drop any pretense of actually calculating μ_2 or μ_o, as needed for Re_2, K or Re_o, and simply define a new simulation parameter in which we seek to retain the known effectiveness of the aforementioned parameters but avoid their ambiguity in rarefied, nonequilibrium flows. Keeping Re_w as previously and replacing T_w/T_o with $H_w/H_o \approx 2 H_w/U_\infty^2$, we avoid the more awkward quantities λ_∞, μ_∞, γ, T_2, and T_o and define

$$\Phi = Re_w (2 H_w/U_\infty^2)^{\xi} \tag{14}$$

where $\xi = f(H_w, U_\infty^2)$ for a given gas and is expected to be related to ω. The relationship of Φ with Re_o and K encourages the belief that Φ is appropriate to the type of flow considered; it remains to be seen if it serves the desired purpose.

SECTION III
EXPERIMENTAL DATA CORRELATION

From Eqs. (2), (4), (6), (10) and (14), the following set of simulation parameters is drawn, assuming γ = constant in the first three:

$$Re_w\,(T_w/T_o)^{\omega-\frac{1}{2}} \qquad Re_w\,(T_w/T_o)$$

$$Re_w\,(T_w/T_\infty)^{\omega-\frac{1}{2}} \qquad Re_w\,(2\,H_w/U_\infty^2)^{\xi}$$

These, plus Re_W alone, are used in presenting a collection of (mostly) hypersonic sphere C_D measurements in Figs. 1 through 5. Data corresponding to M_∞ as low as three are included so as to determine if the $M_\infty >> 1$ assumption is unduly restrictive in the foregoing simplifications of the scaling parameters. Values of ω were varied to correspond to the temperatures represented in each case, but ξ was taken to be constant. The identity of points on all figures is given in Fig. 5.

No comment is offered concerning the results shown in Fig. 1 through 4 beyond the observation that none of the dimensionless numbers derived from the currently used parameters seems adequate to correlate the diversified data used to test them. On the other hand, in Fig. 5 one sees a better degree of correlation when using Φ; in fact, it is not markedly poorer than the experimental scatter in most sets of data represented. The rms $\Delta(C_D/C_{D_{fm}})$ reflecting failure to attain perfect correlation with Φ is ± 0.043; whereas, the average rms $\Delta(C_D/C_{D_{fm}})$ owing to scatter in all sets of data is ± 0.032 and the poorer data scatter to a much worse extent. These numbers were obtained by use of a digital computer program for statistical analyses of experimental data and curve fits.

It will be noted that $\xi = 0.6$ has been found to be the best compromise for all data in Fig. 5. Concern that the lower velocity data might have influenced this choice prompted a look at only those cases where $M_\infty > 8$ and $2H_W/U_\infty^2 < 0.18$. Then the same rms $\Delta(C_D/C_{D_{fm}})$ resulted when either $\xi = 0.5$ or 0.6.

For convenience, the very simple expression

$$C_D/C_{D_{fm}} \approx 1 - 0.09\,\Phi^{\frac{1}{2}} \tag{15}$$

which is plotted in Fig. 5, can be used as a representation of the correlated data for $\Phi < 20$, i.e., within the near-free-molecule and merged-layer flow regimes. If one wished, another empirical expression could

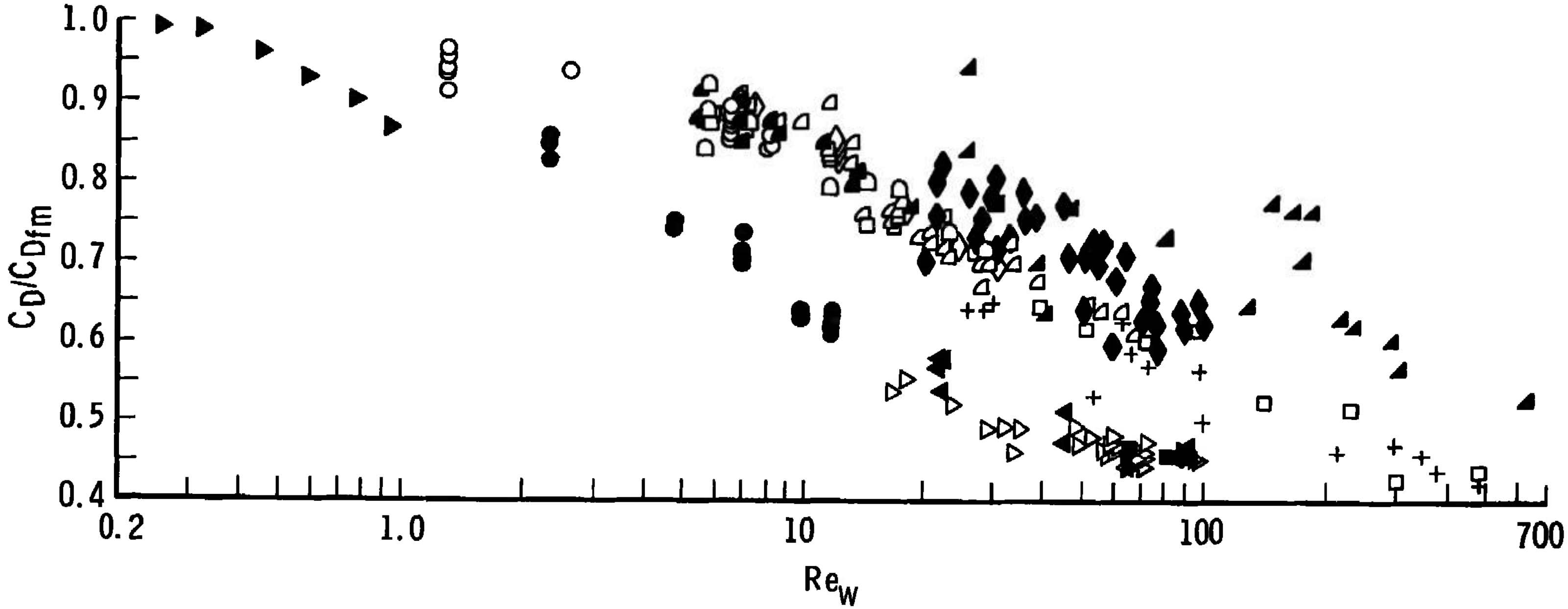

Fig. 1 Correlation with Re_w

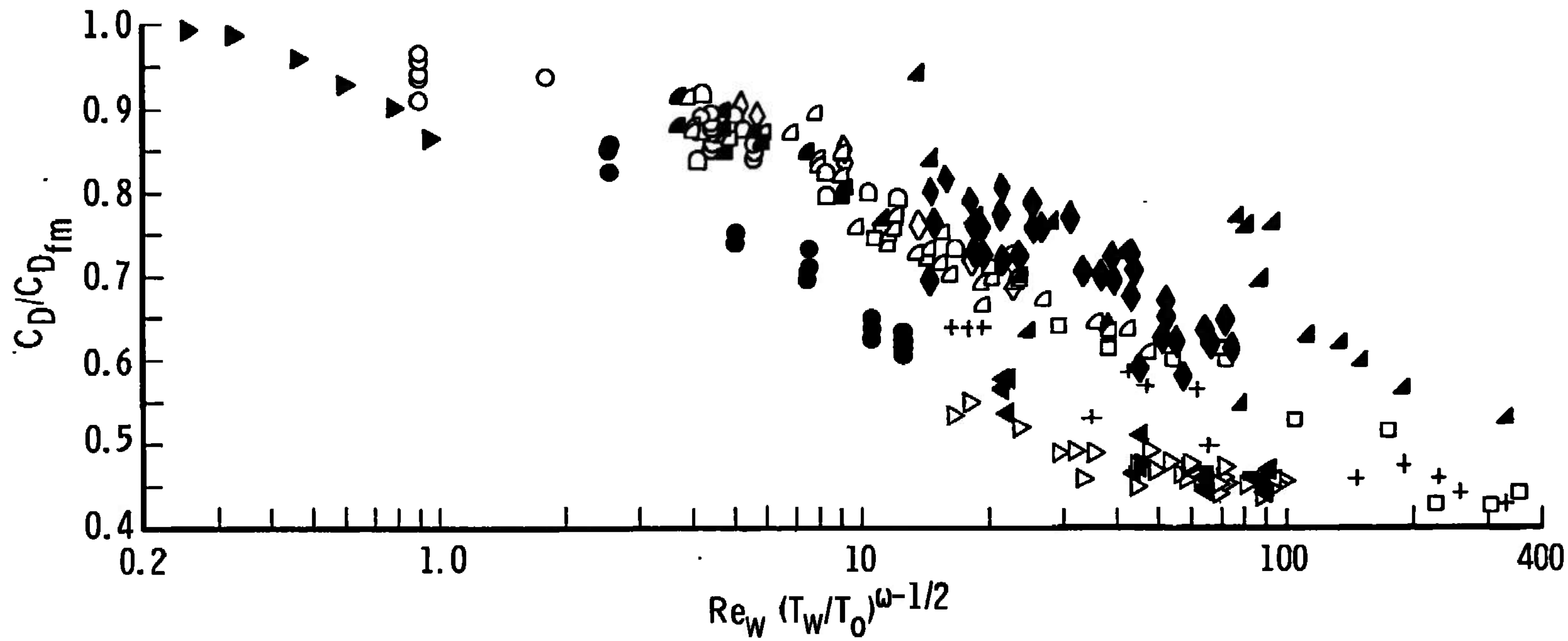

Fig. 2 Correlation with $Re_w\ (T_w/T_o)^{\omega-½}$ (Related to a_o)

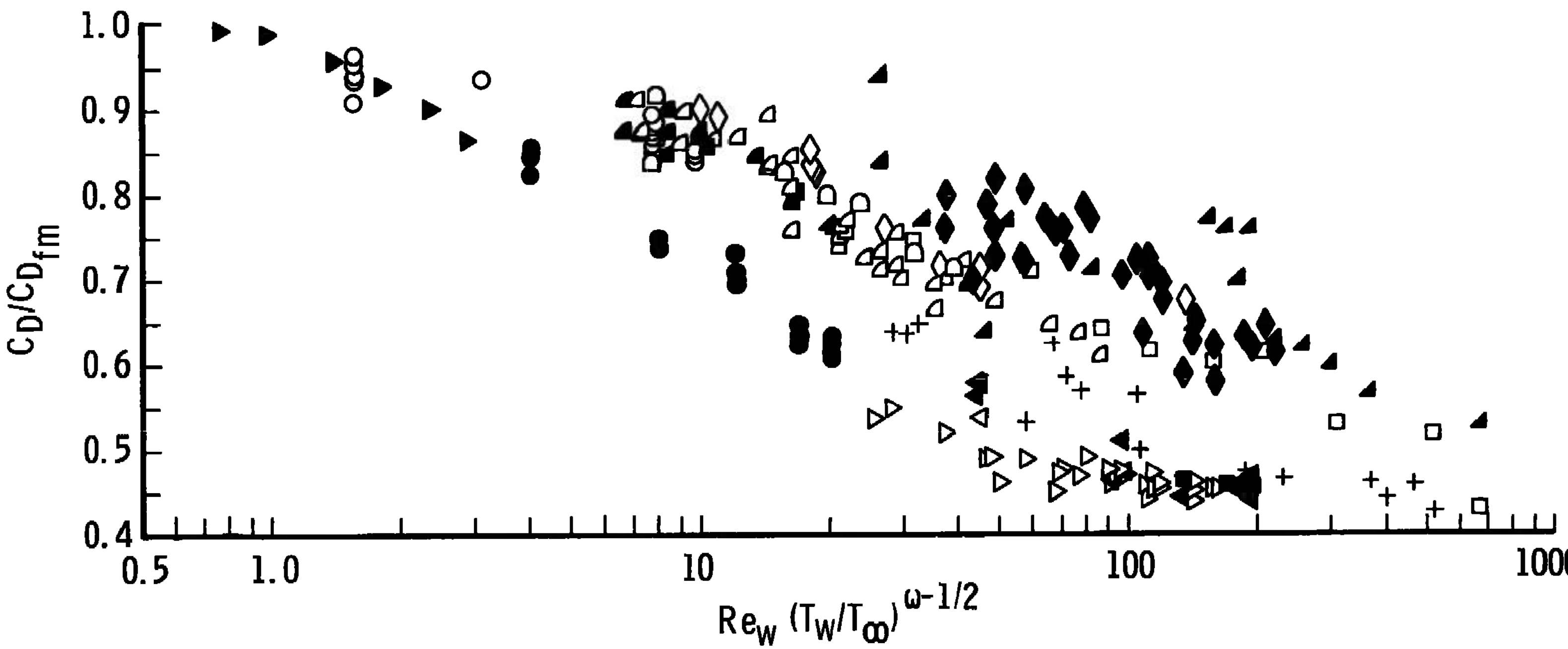

Fig. 3 Correlation with $Re_w(T_w/T_\infty)^{\omega-1/2}$ (Related to S_w/Kn_∞ and Kn_w^{-1})

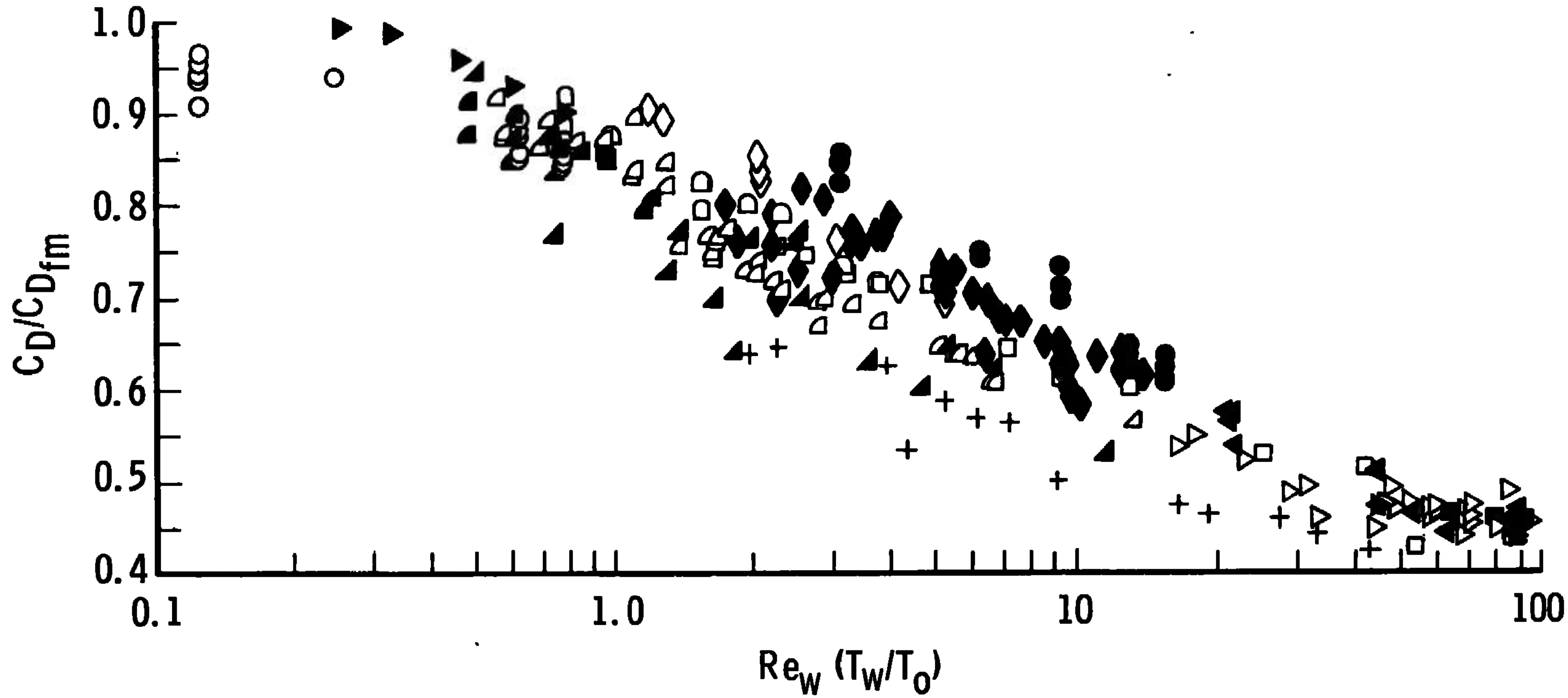

Fig. 4 Correlation with $Re_w\ (T_w/T_o)$ (Related to $\bar{V}_\infty^{-2}$)

	M_∞	T_w/T_∞	$(2H_w/U_\infty^2)$	Ref.		M_∞	T_w/T_∞	$(2H_w/U_\infty^2)$	Ref.
◢	10.5 - 10.7	1.98 - 2.05	0.0880 - 0.0885	4	■	5.50 - 5.61	7.04 - 7.30	1.13 - 1.14	8
◿	10.6 - 10.8	2.24 - 2.30	0.0976 - 0.0995	4	▶	8.30	15.0	1.01	9
⌂	10.5 - 10.6	3.03 - 3.04	0.134 - 0.136	4	+	8.09 - 9.40	1.30	0.0510 - 0.748	10
◊	10.7 - 10.8	3.96 - 4.00	0.169 - 0.171	4	○	9.96	1.92	0.0961	Present
□	14.6 - 15.1	7.2	0.180	7	◢	12.0 - 21.92	1.06 - 1.82	0.0118 - 0.0452	Present
◀	5.48 - 5.91	6.99 - 8.00	1.12 - 1.14	8	●	4.10	4.54	1.33	Present
▷	3.15 - 4.05	3.03 - 4.28	1.28 - 1.47	8	◆	17.4 - 21.0	4.84 - 11.1	0.0797 - 0.165	Present

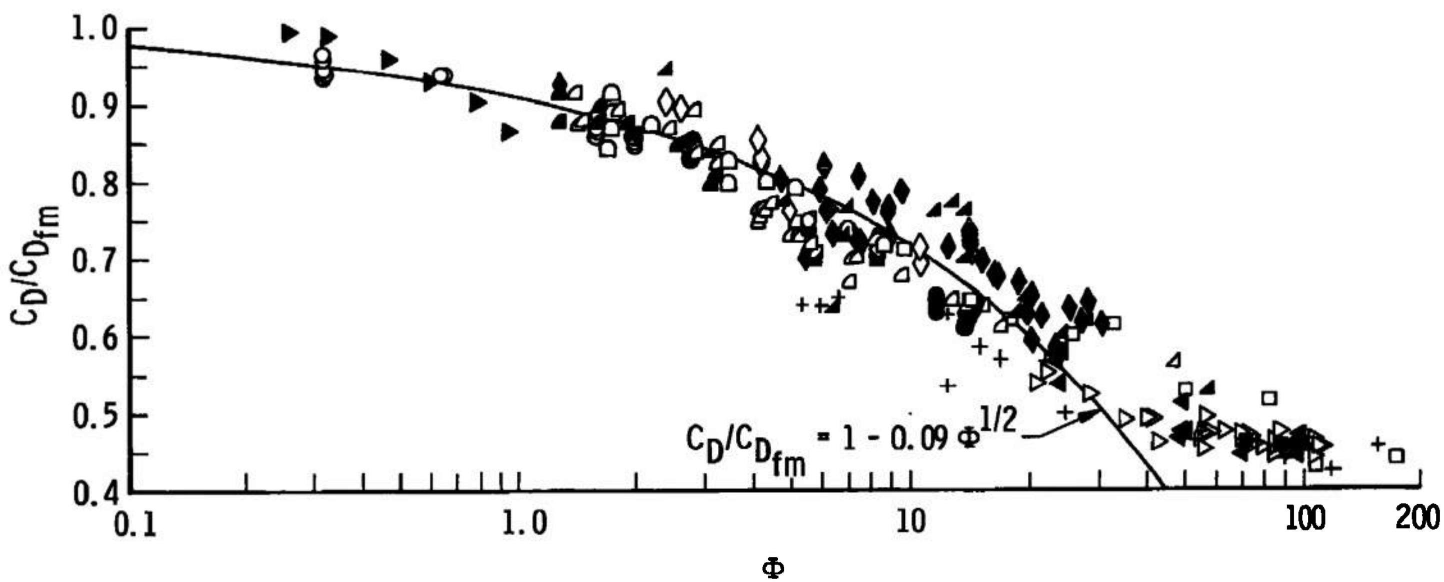

Fig. 5 Correlation with Φ (Related to Re_o, K^2, and Kn_∞^{-1}) Using $\xi = 0.6$

be found which would extend all the way to continuum flow. One such is

$$C_D/C_{D_{fm}} = \left[\frac{A\,\Phi^B + 1}{A\,\Phi^B + (C_{D_{fm}}/C_{D_i})^2}\right]^{1/2} \tag{16}$$

where A = 26.95, B = -0.8714, and when $M_\infty >> 1$, $C_{D_{fm}}/C_{D_i} = 2.3$. However, Eqs. (15) and (16) should not be given undue attention at this time.

SECTION IV
CONCLUDING REMARKS

A significant practical aspect of this question is to be seen in the need to predict full-scale hypervelocity-flight drag on the basis of subscale laboratory experiments wherein flow conditions often are not duplicated. Unfortunately, additional unknowns are represented by gas/surface interaction and atmospheric properties at high altitudes. Only the aerodynamic scaling is addressed in this paper. It also is recognized that the body shape discussed, having only one characteristic length, simplified the problem and inclusion of cones and other shapes presenting a choice of possible characteristic lengths would add to the problem.

These first results suggest that Φ serves better for sphere drag correlations than anything else considered herein. However, measurements with less scatter are needed for further assessment of the simulation parameter. To be most useful, these measurements should be made under hypervelocity cold-wall conditions. They possibly would bring to light any dependence of ξ on the enthalpy levels, which has not been attempted here because of the evident data scatter. If variable γ were a feature of such data this factor also could be evaluated.

REFERENCES

1. Sherman, F. S., Willis, D. R., and Maslach, G. J. "Nearly Free Molecular Flow: A comparison of Theory and Experiment." Proceedings of the 11th International Congress for Applied Mechanics (1964) (H. Görtler, ed.), Springer-Verlag, Berlin, 1966.

2. Kogan, M. N. and Degtyarev, L. M. "On The Computation of Flow at Large Knudsen Numbers." Astronautica Acta, Vol. 11, 1965, p. 36-42.

3. Baker, R. M. L., Jr. and Charwat, A. F. "Transitional Correction to the Drag of a Sphere in Free Molecule Flow." Physics of Fluids, Vol. 1, No. 2, 1958, pp. 73-81.

4. Kinslow, M. and Potter, J. L. "Drag of Spheres in Rarefied Hypervelocity Flow." AIAA Journal, Vol. 1, 1963, pp. 2467-2473.

5. Tsien, H. S. "Superaerodynamics, Mechanics of Rarefied Gases." Journal of the Aeronautical Sciences, Vol. 13, No. 1, 1946, pp. 653-664.

6. Cheng, H. K. "The Blunt-Body Problem in Hypersonic Flow at Low Reynolds Number." Cornell Aeronautical Laboratory Report CAL AF-1285-A-10, June 1963.

7. Geiger, R. E. Report R635D2-3, Missile and Space Vehicle Department, General Electric Company, 1963.

8. Aroesty, J. "Sphere Drag in a Low-Density Supersonic Flow." In Rarefied Gas Dynamics (J. A. Laurmann, ed.), Vol. 2, Academic Press, New York, 1963, pp. 261-277.

9. Smolderen, J. J. "Final Scientific Report - Low Density High Temperature Gas Dynamics, November 1966-October 1967." von Kármán Institute for Fluid Dynamics, Rhode-St. Genese, Belgium, 1967.

10. Bailey, A. B. "High-Speed Sphere Drag in the Transition-Flow Regime in an Aeroballistic Range." In Rarefied Gas Dynamics (C. H. Brundin, ed.), Vol. 2, Academic Press, New York, 1967, pp. 1127-1144.

APPENDIX
MEASURED SPHERE DRAG COEFFICIENTS AND EXPERIMENTAL CONDITIONS FOR 1968 AEDC DATA

New experimental data not previously published are presented in Tables I-a through d for the convenience of users. Values of $C_{D_{fm}}$ have been computed on the basis of fully diffuse, fully accommodated gas-surface interaction. Viscosities used in computing Reynolds numbers are from Svehla (Ref. I-1) and, in the range of T_∞ for nitrogen in Tunnels L and M, are on the order of five percent higher than viscosities taken from the NBS tables (Ref. I-2). In regard to T_∞ in air in Range G and T_W in all cases represented here, agreement between the two references is on the order of one percent. Enthalpies corresponding to T_W which were used in computing Φ were taken from Ref. I-2.

REFERENCES

I-1. Svehla, Roger A. "Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures." NASA TR R-132, Washington, 1962.

I-2. Hilsenrath, Joseph, et al. "Tables of Thermal Properties of Gases." National Bureau of Standards Circular 564, Washington, D. C., 1955.

TABLE I
SPHERE DRAG COEFFICIENTS
a. AEDC Tunnel L (Heated Flow)

C_D	$C_D/C_{D_{fm}}$	U_∞, ft/sec	M_∞	Re_∞	T_w/T_∞	Re_w	Φ	Symbol
2.06	0.937	8314	9.96	4.00	1.92	2.60	0.64	○
2.06	0.937	8314	9.96	4.00	1.92	2.60	0.64	
2.00	0.910	8314	9.96	2.00	1.92	1.30	0.32	
2.07	0.840	8314	9.96	2.00	1.92	1.30	0.32	
2.06	0.937	8314	9.96	2.00	1.92	1.30	0.32	
2.10	0.955	8314	9.96	2.00	1.92	1.30	0.32	
2.07	0.940	8314	9.96	2.00	1.82	1.30	0.32	
2.12	0.864	8314	9.86	2.00	1.92	1.30	0.32	
1.94	0.882	8314	9.96	10.00	1.92	6.51	1.60	
1.97	0.895	8314	9.86	10.00	1.92	6.51	1.60	
1.88	0.855	8314	9.86	10.00	1.92	6.51	1.60	
1.91	0.869	8314	9.86	10.00	1.92	6.51	1.60	
1.92	0.873	8314	9.96	10.00	1.92	6.51	1.60	
1.88	0.855	8314	9.96	10.00	1.92	6.51	1.60	
1.87	0.850	8314	9.96	10.00	1.92	6.51	1.60	
1.91	0.869	8314	9.96	10.00	1.92	6.51	1.60	
1.92	0.873	8314	9.96	10.00	1.92	6.51	1.60	
1.88	0.855	8314	9.96	12.50	1.92	8.14	2.00	
1.88	0.855	8314	9.96	12.50	1.92	8.14	2.00	
1.88	0.855	8314	9.96	12.50	1.92	8.14	2.00	
1.85	0.841	8314	9.96	12.50	1.92	8.14	2.00	
1.86	0.845	8314	9.96	12.50	1.92	8.14	2.00	

b. AEDC Range G

C_D	$C_D/C_{D_{fm}}$	U_∞, ft/sec	M_∞	Re_∞	T_w/T_∞	Re_w	Φ	Symbol
1.11	0.529	20870	18.44	722.50	1.20	636.00	57.62	▲
1.26	0.600	21120	18.67	306.40	1.08	281.00	24.39	
1.46	0.629	20590	18.18	226.00	1.06	218.00	18.65	
1.62	0.772	21590	19.07	169.30	1.21	148.00	12.93	
1.47	0.700	23211	20.50	194.80	1.19	174.00	13.81	
1.53	0.729	21544	19.05	89.00	1.15	80.60	6.85	
1.60	0.761	24338	21.45	208.20	1.19	186.00	13.95	
1.60	0.762	24850	21.92	179.00	1.10	167.50	11.68	
1.78	0.839	16138	14.21	28.60	1.17	25.60	3.11	
2.00	0.942	19260	16.90	27.40	1.08	26.00	2.43	
1.66	0.771	13650	12.00	36.40	1.27	30.80	4.80	
1.65	0.764	15500	13.90	63.00	1.54	46.60	7.01	
1.50	0.697	14950	13.16	50.10	1.42	39.20	5.86	
1.64	0.766	14510	12.78	22.10	1.27	18.70	2.71	
1.32	0.623	17070	15.00	298.00	1.28	239.00	28.63	
1.22	0.568	16405	14.40	488.20	1.82	309.00	47.95	
1.39	0.650	16005	14.10	190.00	1.67	128.00	19.45	
1.37	0.638	15592	13.70	60.70	1.69	40.60	6.40	

TABLE I (Continued)

c. AEDC Tunnel L (Unheated Flow)

C_D	$C_D/C_{D_{fm}}$	U_∞, ft/sec	M_∞	Re_∞	T_w/T_∞	Re_w	Φ	Symbol
1.88	0.636	2234	4.10	43.20	4.54	11.69	13.87	●
1.80	0.616	2234	4.10	43.20	4.54	11.69	13.87	
1.80	0.616	2234	4.10	43.20	4.54	11.69	13.87	
1.78	0.610	2234	4.10	43.20	4.54	11.69	13.87	
1.82	0.623	2234	4.10	43.20	4.54	11.69	13.87	
1.83	0.627	2234	4.10	43.20	4.54	11.69	13.87	
1.85	0.634	2234	4.10	36.30	4.54	9.82	11.65	
1.83	0.627	2234	4.10	36.30	4.54	9.82	11.65	
1.90	0.650	2234	4.10	36.30	4.54	9.82	11.65	
1.86	0.636	2234	4.10	36.30	4.54	9.82	11.65	
2.05	0.702	2234	4.10	26.00	4.54	7.03	8.35	
2.04	0.698	2234	4.10	26.00	4.54	7.03	8.35	
2.04	0.698	2234	4.10	26.00	4.54	7.03	8.35	
2.14	0.733	2234	4.10	26.00	4.54	7.03	8.35	
2.08	0.712	2234	4.10	26.00	4.54	7.03	8.35	
2.08	0.712	2234	4.10	26.00	4.54	7.03	8.35	
2.19	0.750	2234	4.10	17.30	4.54	4.68	5.55	
2.18	0.740	2234	4.10	17.30	4.54	4.68	5.55	
2.16	0.740	2234	4.10	17.30	4.54	4.68	5.55	
2.43	0.858	2234	4.10	8.65	4.54	2.34	2.78	
2.41	0.825	2234	4.10	8.65	4.54	2.34	2.78	
2.47	0.848	2234	4.10	8.65	4.54	2.34	2.78	
2.47	0.846	2234	4.10	8.65	4.54	2.34	2.78	
2.48	0.850	2234	4.10	8.65	4.54	2.34	2.78	

TABLE I (Concluded)
d. AEDC Tunnel M

C_D	$C_D/C_{D_{fm}}$	U_∞, ft/sec	M_∞	Re_∞	T_w/T_∞	Re_w	Φ	Symbol
1.36	0.619	8909	18.43	512.08	9.57	89.87	27.52	⧫
1.40	0.635	9370	18.39	466.42	8.62	88.81	25.59	
1.37	0.622	9584	18.37	387.83	8.23	76.56	21.47	
1.28	0.581	9098	17.64	398.04	8.40	77.22	23.05	
1.38	0.627	9592	17.64	338.27	7.56	70.83	19.85	
1.43	0.650	9704	17.62	340.44	7.36	73.09	20.20	
1.35	0.814	8846	18.82	593.14	10.11	99.82	30.83	
1.42	0.645	9311	18.77	537.94	9.10	98.28	28.54	
1.40	0.637	9435	18.42	270.56	8.53	51.92	14.84	
1.30	0.592	8158	18.17	377.82	11.09	59.20	20.15	
1.60	0.726	11692	17.97	229.46	5.39	63.65	14.06	
1.58	0.710	11769	17.91	229.72	5.18	64.89	14.18	
1.58	0.717	10735	17.43	122.28	5.90	31.19	7.64	
1.86	0.755	10911	17.86	146.60	6.00	38.90	8.86	
1.70	0.770	11304	18.13	173.23	5.76	45.00	10.36	
1.67	0.759	11357	18.18	148.11	5.73	38.81	8.83	
1.73	0.787	11421	17.89	97.51	5.49	26.26	5.97	
1.67	0.758	11736	17.65	97.69	5.05	28.03	6.17	
1.77	0.806	10886	17.95	123.80	6.09	30.81	7.42	
1.60	0.728	10811	17.50	104.32	5.86	26.72	6.49	
1.76	0.800	11688	17.51	74.90	5.03	21.62	4.78	
1.67	0.760	11357	17.51	73.28	4.84	21.77	4.98	
1.59	0.724	10611	17.80	233.51	6.31	56.60	14.05	
1.49	0.679	9931	18.10	285.14	7.43	60.88	16.36	
1.48	0.671	10348	18.36	332.95	7.04	74.05	18.94	
1.55	0.703	9483	20.20	354.30	10.11	50.96	14.14	
1.53	0.695	9435	20.80	400.40	10.42	54.79	15.30	
1.48	0.673	9436	21.00	452.60	11.05	59.41	16.59	
1.55	0.706	9666	19.10	277.60	8.75	46.24	12.54	
1.60	0.728	9667	19.20	162.90	8.81	26.93	7.30	
1.70	0.773	9707	20.00	193.90	9.48	29.77	8.03	
1.60	0.728	9634	20.50	229.60	10.12	32.97	8.98	
1.73	0.788	9599	21.00	259.00	10.70	35.20	9.63	
1.80	0.818	9634	20.60	155.40	10.21	22.15	6.03	
1.54	0.698	9646	20.00	133.20	9.65	20.08	5.46	

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13 ABSTRACT

The current use of several different dynamic simulation parameters for correlating bluff body drag coefficient data is reviewed in terms of the need for a parameter which is both effective and does not contain any quantities whose values are uncertain in hypervelocity real-gas nonequilibrium flows. Such a nondimensional number or parameter is suggested and its effectiveness for correlating a variety of both previously published and new sphere drag data is assessed.

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